

FACTORS AFFECTING THE ELECTRIC CHARGE ACQUIRED BY AN ICE SPHERE MOVING THROUGH NATURAL SNOWFALL¹

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ABSTRACT

The factors affecting the electric charge acquired by an ice sphere moving through natural snowfall have been investigated experimentally. When graupel particles were in the air the sphere always received a positive charge. If graupel was not present the sign of the charge appeared to be related to the direction of the atmospheric electric field. When the field was directed downwards the ice sphere received negative charge, and when the field was directed upwards the sphere received positive charge.

The results are explained in terms of the direct transfer to the ice sphere of some of the net charge on the ice particles in the air making a glancing contact with the ice sphere. The charges that an ice sphere received by this mechanism appeared to be much larger than any charges that might have been generated by asymmetrical rubbing between the ice particles in the air and the surface of the ice sphere.

1. INTRODUCTION

In several theories of thunderstorm electrification hailstones play a central role in the generation and separation of the electric charge. In these theories various mechanisms are proposed whereby hailstones would receive a net negative charge as they fell through a cloud while some of the small cloud particles would receive a net positive charge. It is then assumed that the hailstones carry the negative charge to the lower regions of the cloud and the smaller positively charged cloud particles are lifted by convection currents to the upper regions of the cloud. However, the exact mechanisms by which hailstones may become charged when moving through clouds is not agreed upon. For example, Reynolds et al. [8] found in laboratory experiments that an ice sphere received appreciable negative charge when it was exposed to a stream of ice crystals and supercooled droplets in co-existence. Since the sphere received negligible charge when the stream consisted entirely of supercooled droplets, they attributed this charging to the collision of the ice crystals with the warm ice sphere. On the other hand, Latham and Mason [3] found in laboratory experiments that the charging of an ice sphere due to the collision of ice crystals was about five orders of magnitude less than that observed by Reynolds et al. However, Latham and Mason reported that an ice sphere received significant charge when it was bombarded with supercooled droplets

larger than 30μ in diameter. In view of their laboratory results, Latham and Mason concluded that the generation and separation of electric charge due to collisions between supercooled droplets and hailstones was the primary mechanism responsible for thunderstorm electrification.

Only a few experimental measurements have been reported of the charges that an ice sphere can acquire when it moves through a cloud of natural ice crystals or supercooled droplets. Latham and Miller [4] investigated the charges acquired by different ice spheres after they had been rotated at various speeds through natural snowfall. Ice spheres with smooth surfaces were found to acquire a positive charge, but spheres with rough surfaces acquired much larger negative charges which increased in magnitude as the surface roughness of the sphere was increased. In both cases the magnitude of the charges acquired by the ice spheres increased markedly as the speed of impact between the ice crystals and the spheres was increased from 4 to 20 m. sec.⁻¹ Latham and Miller explained these results in terms of charge transfer due to temperature differences produced by the asymmetrical rubbing of the snowflakes on the surface of the ice sphere. More recently, Hobbs and Burrows [2] measured the charge acquired by an ice sphere after it had been whirled through various types of natural clouds. It was found that the sphere received an appreciable charge only if ice were present in the cloud. Provided the air temperature was -4°C . or lower the charge on the sphere was generally negative. However, when the air temperature was above -4°C . the charge on the sphere had the same sign as the charge

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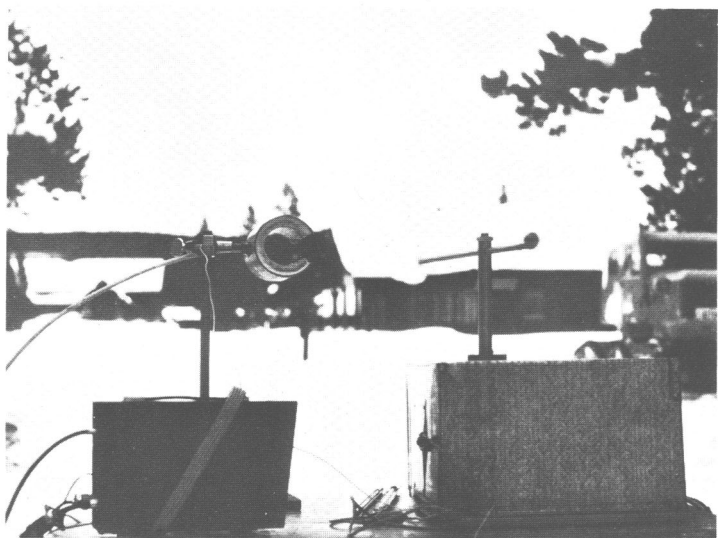


FIGURE 1.—Photograph of experimental apparatus.

on the particles in the air. When graupel was present the ice sphere always received a large positive charge. A systematic increase in the magnitude of the charging with increasing velocity of impact and surface roughness of the sphere was not observed in these experiments.

It is clear from the field observations of Latham and Miller and those of Hobbs and Burrows that the collision of natural airborne snowflakes or ice crystals with an ice sphere can result in the latter receiving considerable electric charge. However, the mechanism by which the sphere receives this charge remains uncertain and there is disagreement as to the factors that control the size and magnitude of the charging of the sphere.

To obtain further information on the charging of an ice sphere moving through a cloud of natural snowflakes, a series of field measurements were made in Yellowstone Park during January 1967. The results of this investigation are reported below.

2. EXPERIMENTAL

Ice spheres about 2.5 cm. in diameter were prepared by freezing water inside a hollow glass ball and breaking away the glass after the water had frozen. The surfaces of these spheres were very smooth but they could be roughened to varying degrees by spraying them with small water droplets from an atomizer. One end of a small wooden stick about 1 mm. in diameter and 2 in. long was frozen into each sphere. The spheres could then be attached to a rigid horizontal arm (fig. 1) by pushing the other end of the stick into a small rubber insulator on the end of the arm. The horizontal arm was attached to an electric motor and by varying the length of the arm the speed of the ice sphere through the air could be varied from 0 to 13 m. sec.⁻¹ In all cases the sphere was

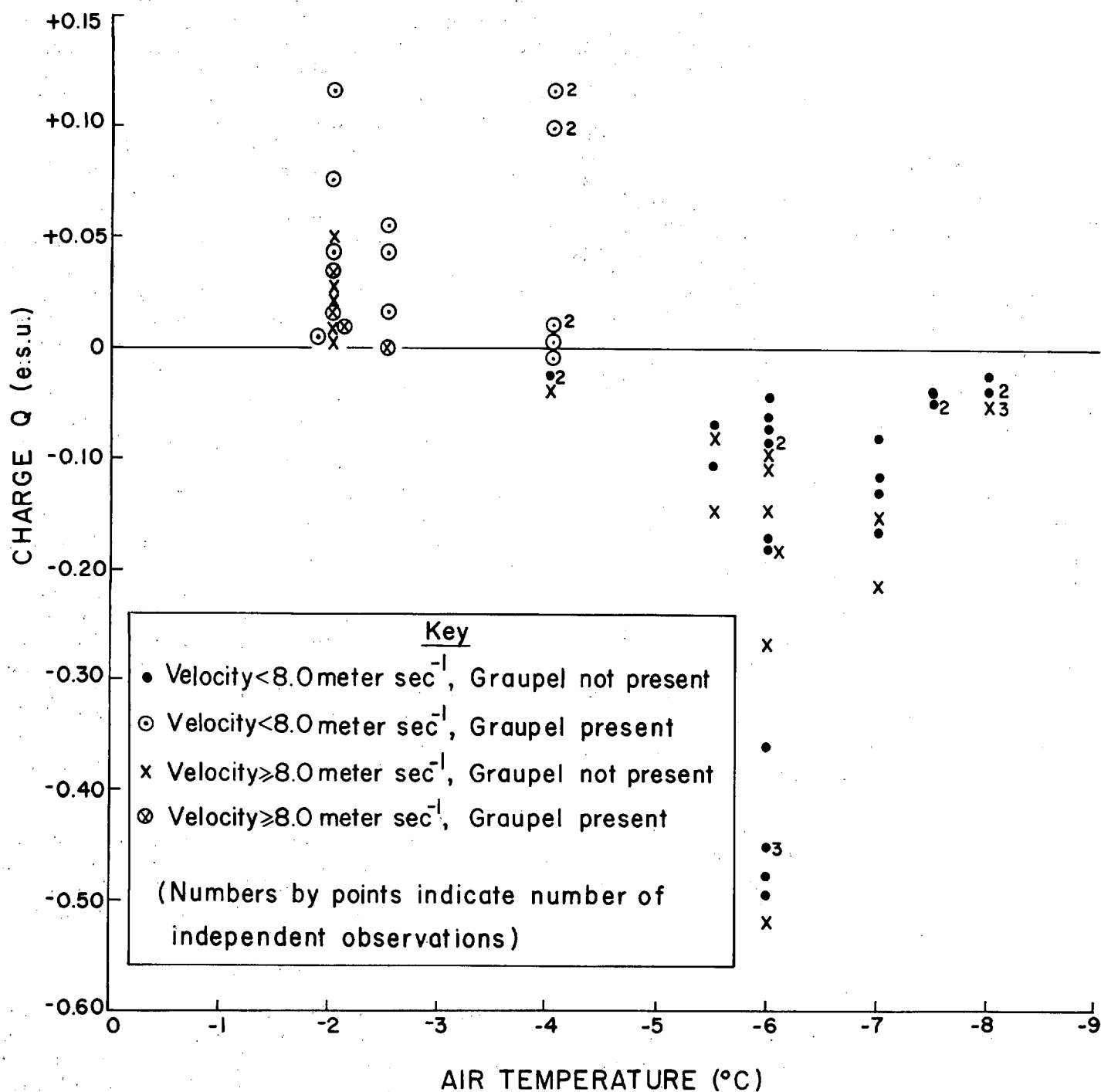
whirled in a horizontal plane 3 ft. above ground level through natural snowfall; water droplets were never present in the air. Inspection of the sphere at the end of each experiment revealed that the snowflakes that collided with the sphere were not collected even when the air temperature was as high as -2°C .

Prior to the start of each experiment the ice sphere was grounded to leak off any charges that it might have acquired. The sphere was then rotated at a known velocity through natural snowfall and the charge acquired by the sphere was measured on each revolution by passing it through an induction can in the form of a hollow cylinder with a slit in its side (fig. 1). The charge induced on the can was then amplified and displayed on a chart recorder. In addition to recording the charge on the ice sphere the time interval between consecutive deflections on the recorder provided a record of the velocity of the sphere. For a given set of environmental conditions the ice sphere quickly acquired a charge which remained fairly steady in magnitude while the sphere was moving through the air at a constant speed. Under these conditions the charge on the sphere was such that the rate of charging was equal to the rate of loss of charge. It should be noted that since the loss of charge from the sphere was due primarily to conduction through the rubber support, the steady charges on the ice spheres in these experiments were not the same as the charges that would have been carried on similar ice spheres falling freely through the snowfall. However, a measure of the rate of charging due to the snowflakes colliding with the ice sphere could be obtained from the magnitude of the charge on the sphere. The response time to changes in the rate of charging was about 1 min.

During the experiments a potential gradient meter was used to obtain simultaneous measurements of the magnitude and direction of the atmospheric electric field. Also, "polyvinyl formal Formvar" replicas of the snow crystals in the air were taken at periodic intervals during each experiment.

3. RESULTS

The sign of the electric charge received by an ice sphere when moving through snowfall was found to depend primarily on three factors, namely, the presence of graupel particles in the air, the direction of the atmospheric electric field, and the temperature of the air. The effect of graupel on the sign of the charge acquired by the ice sphere was quite clear: whenever graupel was in the air the sphere invariably received a net positive charge. In the absence of graupel the sign of the charge on the ice sphere seemed to correlate best with the direction of the atmospheric electric field. A downward directed electric field (i.e., the normal condition in the atmosphere) was accompanied by negative charge on the sphere and an upward electric field by a positive charge on the sphere. On some occasions the direction of the atmospheric electric field fluctuated rapidly and the sign of the charge on



not be concluded that the air temperature, per se, was responsible for the observed change in the sign of the charges on the ice spheres at -4°C .

The results shown in figure 2 are divided into two groups, those for which the speed of the sphere was less than 8 m. sec.^{-1} and those for which the speed was greater than or equal to 8 m. sec.^{-1} . At a given temperature the charges that were measured on the spheres whirled at the higher speeds were generally more negative than those on the spheres whirled at the lower speeds. This result is somewhat misleading for even if the charge received by an ice sphere due to an ice crystal colliding with it were independent of the speed of impact, the rate of charging of the sphere would increase with increasing speeds due to the greater number of crystals colliding with it in unit time. However, the ratio of the charge on the sphere to its speed (Q/V) should be proportional to the charge received by the ice sphere per ice crystal collision and the density of the snow crystals in the air. The ratio Q/V is shown in figure 3. Those spheres whirled at higher speeds generally acquired charges of the same sign as those whirled at lower speeds, but the magnitudes of Q/V were generally *smaller* at the higher speeds.

Experiments to determine the effect of surface roughness on the charge acquired by the sphere were inconclusive. In some cases increasing the roughness of the surface of the ice sphere resulted in an increase in the negative charge on the sphere, but on other occasions the charge on the sphere appeared to be independent of the surface roughness.

4. DISCUSSION

The experimental results described above should be compared with those of Latham and Miller [4]. These workers reported that the main factors governing the charging of an ice sphere moving through natural snow crystals were the surface roughness of the sphere and the speed with which the sphere was whirled through the air. In contrast, our results show that if an ice sphere is whirled through a cloud of falling snow crystals at a few feet above ground level the charge acquired by the sphere is determined primarily by environmental parameters, the most important of which are the nature of the ice particles in the air, the direction of the atmospheric electric field, and the temperature of the air.

Latham and Miller ascribed the charging of the ice sphere to asymmetrical frictional rubbing between ice crystals in the air and the surface of the ice sphere, the charge transfer being the result of the diffusion of protons from the warmer ice sphere to the colder ice crystals as predicted by the temperature-gradient theory of Brook [1] and Latham and Mason [3]. However, a rough calculation made by Latham and Miller indicated that the charges that they measured on the ice spheres were three orders of magnitude larger than the value predicted by the temperature-gradient theory. To account for this discrepancy they suggested that the charge generation due

to the temperature gradient between the ice sphere and a colliding ice crystal was enhanced by the roughness of the sphere and the high speeds of impact. An enhancement effect of this kind had previously been observed in the laboratory by Latham and Stow [5].

The experimental results reported by Hobbs and Burrows [2] on the charging of ice spheres moving through natural ice crystal clouds and snowfall are similar to those reported in this paper but they are somewhat more variable. These workers found that when graupel was present in the air the sphere always received a comparatively large positive charge. In the absence of graupel and when the air temperature was above -4°C . the sphere received a net positive charge more often than negative, but at temperatures of -4°C . or below the reverse was true. The charging of a sphere was not strongly dependent on the speed with which it was whirled through the air and varying the surface roughness of the sphere did not appear to affect the charging in any systematic way. Hobbs and Burrows observed that for air temperatures above -4°C . the sign of the charge on the sphere was the same as the net charge on the ice particles in the air, and they suggested that under these conditions the sphere was charged as a result of the charged ice particles sticking to its surface. However, for temperatures of -4°C . and below this simple correlation was not apparent and the charging of the sphere was attributed to asymmetrical rubbing of the ice crystals on the surface of the ice sphere.

The experimental results described in this paper are most easily explained if it is assumed that at all temperatures the principal mechanism for the charging of the ice sphere was the direct transfer to the sphere of some of the net charge on each of the ice particles making a glancing contact with it. For example, there is a considerable body of experimental evidence that graupel particles carry a net positive charge (MacCready and Proudfit [6], Magono and Orikasa [7]) and this would explain the fact that when graupel particles were in the air the ice sphere always acquired a positive charge. The observed correlation between the sign of the charge on a sphere and the direction of the atmospheric electric field is also readily explained in terms of the above idea, for the sign of the charge on snow crystals bears a "mirror image" relationship to the direction of the atmospheric electric field (Wilson [9], Magono and Orikasa [7]). Therefore, when the electric field is directed downwards the ice sphere should receive a net negative charge from the snow crystals colliding with it, and when the field is upwards the sphere should become positively charged. These conclusions are in agreement with the experimental observations. The tendency for the magnitude of Q/V to be smaller at higher impact speeds (fig. 3) may also be rationalized in terms of shorter times of contact between the crystals and the sphere; however, the experimental results on this point are not conclusive.

It would appear, therefore, that in our experiments the

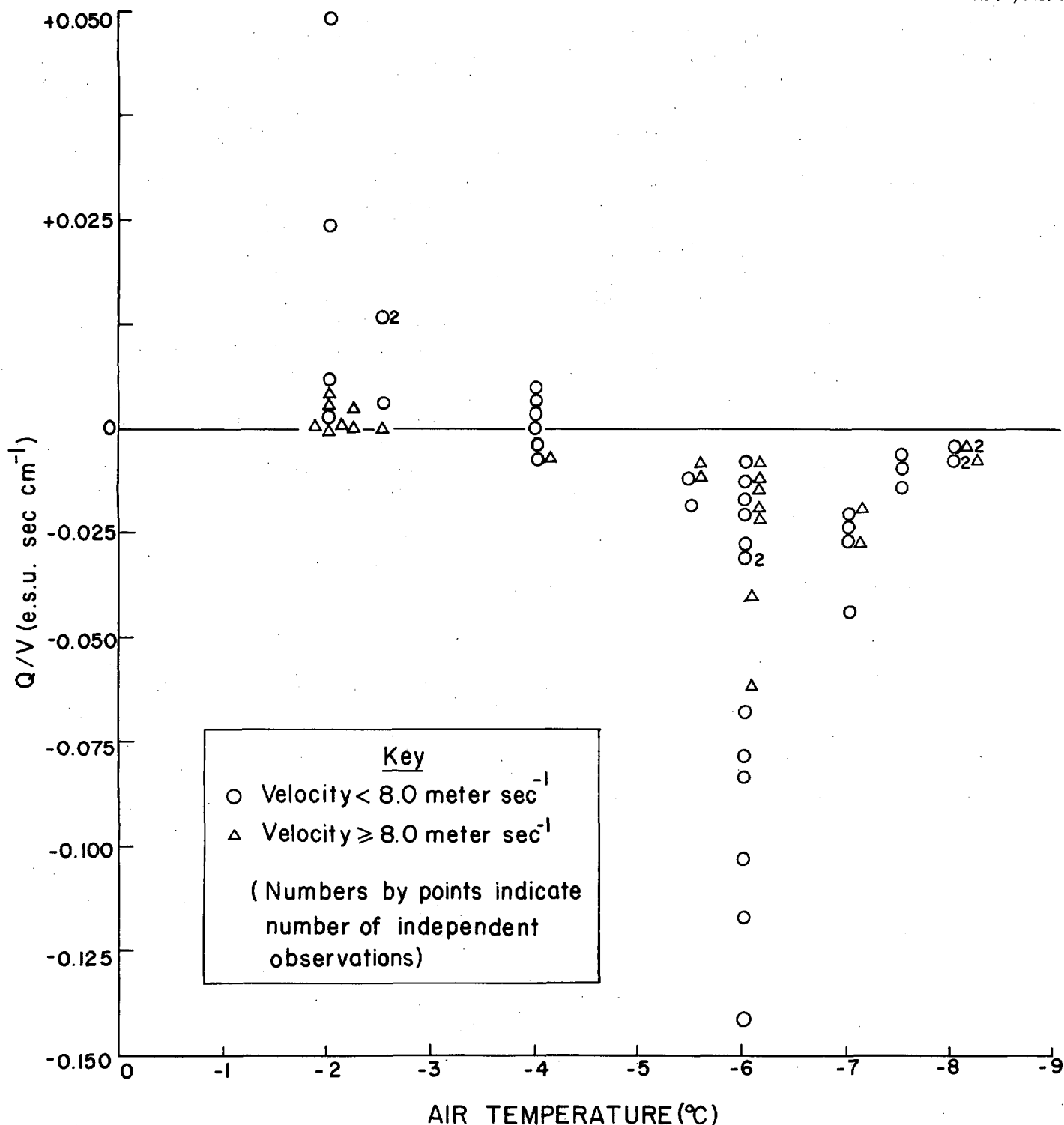


FIGURE 3.—The ratio of the steady charge Q to the speed V for ice spheres whirling through natural snowfall. (Note: Expanded scale has been used for positive values of Q/V .)

generation of charges due to asymmetrical rubbing between the crystals and the ice sphere was much less important than the charges which were transferred directly to the sphere from the charged snow crystals. However, it must be noted that no attempt was made in these experiments to raise the overall surface temperature of the ice sphere

above that of the environmental air temperature. In natural clouds, the surface temperature of a hailstone can be considerably higher than that of the environment due to the release of latent heat from the droplets freezing onto the hailstone. Under these conditions it is possible that the generation of charge due to the differences in

temperature between the surface of the hailstone and the ice crystals colliding with it is significant. These ideas are supported by the laboratory measurements of Reynolds et al. [8] who found that the collision of ice crystals with an ice sphere produced a significant charging only if supercooled droplets were also present in the air. From the figures given by Reynolds et al. [8] and Hobbs and Burrows [2] it would appear that when a hailstone is falling through a natural cloud consisting of supercooled droplets and ice crystals, the charge that the hailstone receives by direct transfer from the charged ice crystals is of the same order of magnitude as the charge it receives as a result of the generation of charge due to the difference in temperature between the colliding crystals and the surface of the hailstone. When the ice crystals in a cloud are charged negatively both of these charging mechanisms will communicate negative charge to the hailstones, but when the crystals are positively charged the two charging mechanisms will oppose one another.

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